Research article: Musculoskeletal injury risk assessment and intervention at a car manufacturer using various ergonomics and biomechanical tools

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Abstract

Background: Musculoskeletal injuries are common diseases among workers causing a substantial economic burden on society. Therefore, assessment of musculoskeletal injury risks during occupational activities is essential for the design of subsequent effective interventions and management programs.

Methods: Risk of three occupational activities performed by one worker in a shot-peening station of a car manufacturing company has been investigated using several biomechanical (i.e., musculoskeletal models such as HCBCF, Regression models, 3DSSPP and AnyBody) and ergonomics (e.g., Washington State tables, WISHA, NIOSH, MAC, Snook's Table, ManTRA, QEC, OWAS, REBA, and RULA) risk assessment tools. The worker's activities involved manual material handling of gearbox shafts and pushing/pulling of a carrier containing these shafts.

Results: Our findings indicated a high risk of musculoskeletal injuries during all activities. Therefore, engineering and administrative interventions were provided. After the interventions, injury risk during pushing and pulling activities was fully managed to a safe zone by using overhead cranes. The lifting task was also rendered within a safe zone through the application of administrative interventions and using an appropriate work table.

Conclusion: Comprehensive risk assessments by biomechanical and ergonomic tools, managed risks to safe levels, and load dynamics effect in risk assessments were considered.

Keywords: biomechanical models, ergonomics tools, interventions, musculoskeletal injury, risk assessment

1. Introduction

Low back pain (LBP) is one of the most significant health concerns worldwide [1-4] and the main cause of absences from work [5-7]. As one of the most common causes of chronic disabilities among people under 45 years old, approximately 85% of the world's population suffer from LBP at least once in their lifetime [8]. LBP is the most common cause of disability in the United States with ~2% of the workers undergoing lumbar surgery annually [9, 10]. In Europe (e.g., the United Kingdom and Sweden), the main reason for health worker absenteeism is also reported to be LBP [10]. The lifetime prevalence of LBP among the Iranian population has been reported to be 25.2% [11]. As a result, LBP is the costliest musculoskeletal disorder among the working population [12-17]. The annual cost of LBP treatments in the United States is estimated at $20-100 billion [18]. The cost of reduced productivity due to LBP over 6 months is also estimated at €4,315 per patient [19]. Altogether, epidemiological investigations indicate the importance of workplace injury risk assessments for effective management of LBP.

Biomechanical risk factors, i.e., loads on the spinal joints and its surrounding active-passive tissues, form one of the main etiologies of LBP and musculoskeletal injuries in occupational activities such as lifting tasks and repetitive/prolonged movements. Practitioners in the field of occupational biomechanics should; therefore, assess risk of musculoskeletal injuries in workplaces and provide effective job interventions to reduce the risk using both ergonomics-based (e.g., the NIOSH Revised lifting equation [20], RULA (the Rapid Upper Limb Assessment) [21] and REBA (the Rapid Entire Body Assessment [22]) as well as biomechanical-based (i.e., musculoskeletal biomechanical models such as 3DSSPP [23]) risk assessment tools. For instance, in 2019, risk of injury associated with repetitive tasks, awkward postures and heavy physical loads at an automotive manufacturing factory was assessed using the popular ergonomics risk assessment tool of RULA [24]. In another study, risk of injury to workers of a manufacturing plant was assessed using three ergonomics tools (a psychosocial questionnaire, the NIOSH Revised Equation, and REBA) without providing any engineering intervention to manage the associated risk [25]. Moreover, risk of injury during manual material handling (MMH) activities in a supermarket was assessed using a biomechanical risk assessment tool, i.e., the AnyBody modelling software [26]. It was suggested that weight of the lifted boxes should be reduced to manage risk of injury.

In all these studies, only few ergonomics- and/or biomechanical risk assessment tools have been used to evaluate risk of injury and, generally, without providing an effective intervention and reassessment of the activities after the intervention. The present study; therefore, aims to assess risk of injury to workers of Megamotor corporation shot-peening station using various ergonomics (e.g., Washington State tables [27], WISHA [27], NIOSH [20], MAC (Manual Handling Assessment Charts [28]), Snook's Table [29], ManTRA (Manual Task Risk Assessment [30]), QEC (Quick Exposure Check [31]), Cycles to failure/Survival chance [32], OWAS (Ovako Working posture Assessment System [33]), REBA, and RULA) and biomechanical (e.g., HCBCF (Hand Calculated Back Compressive Force), Regression models of Arjmand et al. [34], Simple polynomial McGill [35], 3DSSPP and AnyBody Modeling System) risk assessment tools. Workers of this workstation are involved with handling of Gearbox shafts (~1.7 kg with a rate of 1200 lifts in a working day of 8 hours) from industrial baskets on a carrier and then pushing/pulling of the carrier, which was hanged from the ceiling into the shot-peening chamber (~673 kg, 11 times per 8-hour working period). After the assessment of injury risk, engineering and administrative interventions are provided and the risk of injury is reassessed to investigate the effectiveness of the applied interventions.

2. Methods

2.1 Motion analysis: In order to use some injury risk assessment tools, motion data from the workplace need to be captured. Since motion capture systems such as optoelectronic devices could not be used in Megamotor Corporation due to logistical limitations, the activities of a 25-year-old worker (weight: 85 kg, height: 190 cm) were photographed and recorded using a digital camera "Figure 1". We assessed the youngest and physically powerful worker in our group, and the results showed that even for him, the risk of injury remained elevated. This suggests that the risk may be similarly high for other workers within the Iranian workforce. However, we do not claim that this individual represents the broader population of Iranian workers. The purpose of this study was to conduct a detailed pilot analysis of task-specific biomechanical impacts, and the findings provide a foundation for future studies with more representative samples. The most critical moment of the occupational activity was considered in each of the three activities (i.e., MMH, pulling and pushing) for subsequent assessments. An open access image processing tool was used to estimate body segment angles and lengths during the activities. Due to data collection limitations, we focused on one worker and three tasks (pushing, pulling, and manual material handling), which together represent the heaviest job demands in the factory under consideration. The participant

chosen was the youngest and physically powerful worker, and although the sample size is small, the methodology used can be scaled up and applied to other occupational tasks. After extracting the angles, the worker's posture was simulated in the AnyBody Modelling System. This allowed for the comparison of the AnyBody model with the actual worker's posture in the images as well as for the proper estimation of hand-load position as required in other tools (e.g., HCBCF).
In addition, acceleration was extracted from the recorded videos. During lifting of the shafts, the maximum acceleration occurred at the beginning of the movement/lifting. Moreover, the accelerated motion during lifting resulted in greater forces applied to the worker compared to the instance the worker lowered the load. Pulling and pushing activities required that worker moved the carrier from rest (zero velocity) by applying force. In these activities, the maximum acceleration experienced by the carrier occurred at the first instance of pushing/pulling; therefore, the force applied by the worker was maximum at this moment.

2.2 Tasks: Workers of this workstation performed lifting, pushing and pulling activities. During the lifting activity, gearbox shafts were picked from industrial baskets, which had already been filled in the heat treatment section and transferred to the shot-peening section. The observed worker experienced the worst posture during the initial phase of lifting, where he had to bend forward by about 100 degrees due to obstacles preventing him from approaching the shafts "Figure 1a". The horizontal and vertical distances of the shafts relative to feet (between the two ankles on the floor) were 55 cm and 30 cm, respectively. The worker lifted four shafts together (i.e., two shafts in each hand with each shaft being 1.7 kg) and bent at a rate of 6 times per minute. The lifting activity was analyzed both statically and dynamically to assess the potential risk of body joint overloading. The acceleration of lifting was estimated to be 1.0 m/s^2. In the static simulation, forces acting on the worker's hand are equal to the weight of the four shafts. To consider the dynamic/inertial effects, based on the D'alembert principle, acceleration of gravity was added to the acceleration of the shafts [36]. In other words, in dynamic simulations, the force on the worker's hands was equal to:

$$F = 4m_{shaft}(a_{gravity} + a_{motion}) \qquad (1$$

where *m* and *a* represent mass and acceleration, respectively. Forces are applied symmetrically in both hands. When the shafts were placed inside the carrier or industrial baskets, acceleration of the shafts was subtracted from the acceleration of gravity, therefore the force exerted on the worker's hands was equal to:

$$F = 4m_{shaft}(a_{gravity} - a_{motion}) \quad (2$$

It can be concluded that the initial instance of lifting of the shaft was the critical point in terms of risk of injury; therefore, this instance was investigated in the present study.

During the pushing and pulling activities, the worker moved a large cylindrical carrier (130 × 100 cm) loaded with the shafts. The weight of the carrier was supported by a roof rail. Eleven times in 8-hour working period, the worker had to push the carrier into the shot-pinning chamber and pull it out after the shot-pinning process. The total mass of the carrier and shafts was approximately equal to 673 kg being moved by an acceleration of 0.5 m/s^2. The force required to overcome the friction between the rails and rollers to accelerate the carrier was equal to:

$$F = F_{friction} + ma \quad (3$$

$$F = \mu(mg) + ma = m(\mu g + a) \quad (4$$

In equation (3) and (4) m is the total mass of carrier and shafts, a is the acceleration of motion of carrier on rail, μ is friction coefficient and g is gravity acceleration. Pulling and pushing differ only in the worker's posture with the exerted force on the worker being identical. The friction coefficient between roller and steel rail varied from 0.05 to 0.07. The coefficient of friction was considered equal to 0.05, the lowest value reported elsewhere [37]. The critical worker's postures during pushing and pulling activities are shown in "Figures 1b and c" while a summary of characteristics of the occupational activities are listed in "Table 1".

2.3 Risk assessment tools: Various ergonomics- and biomechanical risk assessment tools were used to assess risk of injury. The ergonomics tools included the NIOSH Revised equation, ManTRA, MAC, REBA, RULA, OWAS, Snook's Table, QEC, Cycles to failure/Survival chance, Washington State Ergonomic and musculoskeletal disorders (MSD) Risk Assessment Checklists and WISHA Lifting Calculator. In addition, seven biomechanical tools including 3DSSPP, AnyBody, Regression models of Arjmand et al. 2011 and 2012 and, Simple polynomial of McGill et al., 1996 and HCBCF were used to estimate spinal joint loads during the occupational activities. Risk zones (low: green zone, moderate: yellow zone, and high: red zone) of each tool is shown in Figure 2: Biomechanical and ergonomics risk assessment tools and their risk zones

2.3.1 Washington State Ergonomic and MSD Risk Assessment Checklists: These are two pre-configured checklists; one tailored to address the caution zone, and the other designed for the hazard zone [27]. Each checklist includes subcategories to address different aspects, such as uncomfortable postures, significant hand forces, highly repetitive motions, recurrent impacts, heavy, frequent, or awkward lifting, and moderate to high levels of hand-arm vibrations. To start the evaluation process, it is recommended that users begin with the caution zone checklist, and consider a task safe only if none of the items are marked. However, if at least one item is checked, users should explore the hazard zone checklist. In this situation, the presence of marked items on the hazard zone checklist or handling weights exceeding the specified limit indicates a high risk of injury. Any item marked in either the caution or hazard zone checklist serves as an immediate indicator, signaling the need for further examination or resolution.

2.3.2: WISHA: The WISHA Lifting Calculator is a practical tool that can be used to assess the risk of low-back injuries during lifting and lowering tasks. It is an adaptation of the Revised NIOSH Lifting Equation, but with simplified measurements. Instead of continuous data, WISHA uses discrete data for vertical and horizontal distances, as well as weight limits for twelve specific hand-load positions. These weight limits are adjusted based on factors such as lifting frequency, total work duration, and twisting. To assess the risk level, a lifting index is calculated by dividing the actual lifted weight by the adjusted weight limit. A lifting index of 1 indicates a safe activity, while values between 1 and 1.5 suggest a moderate risk level, and values exceeding 1.5 indicate a high-risk scenario.

2.3.3. NIOSH: The revised NIOSH lifting equation is a valuable tool for assessing the potential risks associated with manual material handling, particularly for the lower back, based on biomechanical, physiological, and psychophysical criteria [20]. The variables within the equation are the hand load's position (horizontal, vertical, or asymmetrical), its vertical lifting distance, lifting frequency, and the quality of hand-to-load coupling. These factors are used to derive a substantiated recommended weight limit for a given lifting operation. A lifting index is subsequently calculated by dividing the actual weight lifted to the recommended weight limit. A lifting index below 1 signifies a safe activity, while values between 1 and 3 indicate a moderate risk, and values exceeding 3 denote a high risk [20].

2.3.4. MAC: The Manual Handling Assessment Charts (MAC) is a tool for assessing risks associated with various manual handling activities, such as lifting, lowering, carrying, and team handling operations. It takes into account critical factors, including the nature of the hand load, task frequency, hand distance from the lower back, the vertical lift zone, torso twisting, side bending, and postural constraints. Unlike many other assessment tools, MAC also considers additional factors such as the quality of grip on the load, the condition of the floor surface, and environmental elements. Each of these factors is assigned a risk score, and the overall score is calculated by aggregating the individual scores of the preceding risk factors. MAC is an effective tool as it identifies areas of concern that require modification, and prioritizes action by targeting the tasks associated with the highest cumulative risk scores.

2.3.5. RULA: The Rapid Upper Limb Assessment (RULA) is a survey method used to assess the risks associated with musculoskeletal disorders in the upper limbs caused by repetitive or prolonged tasks. It classifies postures and movements of workers into four action levels and helps to identify high-risk positions that may lead to discomfort or injury. RULA allows the evaluator to assess only the worst-case posture of one employee at one point in time, requiring the use of representative postures. RULA provides a rapid evaluation of posture and loads of the left or right side of body, by analyzing joint angles, forces, and activity duration, without requiring specialized equipment.

2.3.6. 3DSSPP: Utilizing worker postures, anthropometric data, and an optimization-driven biomechanical model encompassing ten trunk muscles, 3D Static Strength Prediction Program (3DSSPP) stands as a robust tool for the prediction of L4-L5 compression and shear loads in occupational activities. It also provides data comparisons to NIOSH guidelines. 3D SSPP is most useful in the analysis of the slow movements that are involved in heavy materials handling tasks. This is because the biomechanical computations assume that the impacts of acceleration and momentum are negligible. To evaluate such tasks, it is best to break the activity down into a sequence of static postures and analyze each one individually. 3D SSPP helps in assessing physical tasks but should be used in conjunction with other criteria and professional judgment for safe and productive job design. "Figure 3" shows Simulated postures using 3DSSPP.

2.3.7. ManTRA: The Manual Task Risk Assessment (ManTRA) is a method designed to assess the risk of musculoskeletal disorders associated with MMH tasks, by dividing the body into four distinct regions, allowing for the independent evaluation of risk factors for each region. ManTRA takes into account various factors, such as time, frequency, movement speed, force, posture, and vibration, in its assessment. The method uses a 5-point scale for five key task characteristics (cycle time, force, speed, awkwardness, and vibration) across different body regions. The cumulative risk score is calculated by adding up the total time, repetition risk, exertion risk, awkwardness, and vibration scores, which range from 1 to 25. If the cumulative risk exceeds 15, ManTRA suggests further investigation, work practice modifications, or implementation of higher-order controls to manage the risk of injury.

2.3.8. OWAS: The Ovako Working Posture Analysis System (OWAS) is a tool that categorizes work postures into predefined categories for the back, arms, and legs. It also takes the weight of the load into consideration when evaluating working postures. Unlike other postural assessment methods, such as RULA or REBA, which primarily analyze individual postures, OWAS evaluates the full range of postures adopted over a task. However, it does not differentiate between the right and left upper limbs, nor does it assess the neck, elbows, and wrists. Nonetheless, this tool can help identify high-risk postures that may lead to musculoskeletal disorders. By doing so, it makes it easier to develop targeted intervention strategies to mitigate ergonomic risks. OWAS is easy to use and practical, making it a valuable tool for anyone looking to assess workplace ergonomics.

2.3.9. QEC: The Quick Exposure Check (QEC) is a straightforward, quick, and user-friendly tool for evaluating physical risk factors through 15 questions that cover aspects such as trunk and upper limb postures, load handling, task duration, visual stress, hand force, and work rhythm/stress. The total score for the back, shoulder/arm, wrist/hand, and neck is determined by the interactions between the exposure levels for the relevant risk factors and their subsequent addition. The exposure scores are then categorized into four categories: Low, Moderate, High, or Very High. Finally, these scores are summed and normalized to establish the QEC whole-body percentage. A QEC whole-body percentage below 40% indicates a safe zone, percentages between 40% and 70% signify a moderate risk, and percentages above 70% indicate a high risk. This tool is suitable for a wide range of tasks as it considers the interaction of musculoskeletal risk factors and involves both workers and practitioners, each completing a separate survey.

2.3.10. REBA: Rapid Entire Body Assessment (REBA) assesses injury risk during MMH tasks by categorizing body segments based on postural characteristics, including static, dynamic, unstable, or rapidly changing positions. Similar to RULA, REBA is highly efficient, offering a quick and user-friendly approach to ergonomic assessments. Its computerized registration is publicly accessible, enhancing its ease of use. However, this tool evaluates one side of the body at a time and does not consider factors like the frequency and duration of the activity. REBA provides guidance through five action levels: the first level indicates a negligible risk (REBA score:1), second level a low risk (REBA score: 2-3), third level a medium risk (REBA score:4-7), fourth level a high risk (REBA score:8-10) and fifth level a very high risk (REBA score:11-15).

2.3.11. Snook's Table: Snook's Table, also known as the Liberty Mutual Manual Materials Handling tables, is an ergonomic assessment tool based on psychophysical principles, designed for two-handed manual tasks that include lifting, lowering, pushing, pulling, and carrying. It provides population-based insights for men and women into task capabilities without risking overexertion. The key inputs include hand load positions, frequency, weight, and other task-specific factors. Notably, Snook's Table does not categorize tasks into explicit risk levels but assumes that a task is safe if it can be performed by the majority of the population (90% of men population), similar to the NIOSH approach. The boundary between moderate and high-risk zones is set at a specified percentage of capable individuals (50% of men population), aiding in the design of safer manual material handling tasks and environments.

2.3.12. AnyBody: AnyBody is a powerful simulation software for analyzing the biomechanics of the human body, offering detailed musculoskeletal models and extensive muscle representation to accurately simulate various postures and movements. Using AnyBody, one can estimate muscle forces, joint forces, and moments during different movements and postures, which provides insights into muscle activation and joint stability. Additionally, AnyBody calculates reaction forces at contact points, such as the ground, as well as forces within ligaments and tendons. It can also determine forces and moments acting on individual body segments. These capabilities make AnyBody a versatile tool for applications in sports biomechanics, ergonomics, rehabilitation, and clinical research.

2.3.13. Regression Equation of Arjmand: Arjmand's Regression Equation is a reliable and user-friendly method to calculate compressive and shear forces on the L4-L5 and L5-S1 lumbar spine discs during lifting activities. It considers various inputs such as thorax flexion angle, lumbar/pelvis ratio, load magnitude, and load position. However, it has certain limitations. It is only useful for symmetric lifting tasks in the sagittal plane, with slow movement speeds, and considers only a limited set of input variables and model responses. Developed through response surface methodology and regression analysis, it provides accurate estimates of intradiscal pressure at the L4-L5 disc, aligning closely with in vivo data collected under similar loadings and postures.

2.3.14. McGill Simple Polynomial: The McGill Simple Polynomial is a biomechanical model that calculates low-back compression forces during 3-D loading tasks, making it suitable for industrial applications where a balance between biological content validity and simplicity is crucial. The model is based on polynomial equations and is excellent at capturing nonlinear spinal behavior. It can be customized to suit individual characteristics and conditions, but this can be a complex process that requires expertise in biomechanics. While the McGill Simple Polynomial offers practicality, it may not suitable for advanced research and clinical applications that demand more complex and comprehensive spine models.

2.3.15. HCBCF: The Hand Calculated Back Compressive Force (HCBCF) equation is used to estimate the compressive forces that weigh on the lower back (L4-L5 disc) during manual material handling tasks. The equation takes into account various factors, such as the weight of the load, lift distance, degree of trunk flexion, and the position of the load relative to the L4-L5 disc. These input variables are easy to measure or estimate in the workplace, which makes the model highly usable. However, it is important to note that the model is best suited for tasks with simple lifting and handling characteristics, basic muscle activation, and a limited set of variables, which can result in imprecise force estimations.

2.3.16. Survival chance: The survival chance equation estimates the probability that a worker can safely perform various occupational tasks without injury or failure under specific conditions based on the magnitude of low-back load and the number of load cycles of the tasks. This equation is derived based on in vitro experiments on spinal segments subjected to cyclic compression loads thereby providing a knowledge on how mechanical loading affects spinal health. A higher survival chance percentage indicates a greater likelihood that a worker can endure the mechanical demands of their job without any injury [32].

3. Results

3.1. Risk assessments before interventions: Most of the tools predicted a high level of risk for the investigated activities in this study. “Table 2” displays the risk assessment states of all tools, while “Figure 4” presents the numerical results of biomechanical-based tools, categorized by both tools and activities. With the exception of McGill's polynomial and ManTRA, all other tools predicted either a cautious or hazardous state. Based on the L5-S1 disc compression estimated by AnyBody, the worker's survival chance was determined to be -52%, with a total cumulative damage of 1.5. These findings highlighted the urgent need for immediate interventions in all activities.

3.2. Intervention: Since most of the tools indicated that the occupational activities under consideration were in the hazard/caution zone (due to awkward postures, excessive forces, and frequent/prolonged activities) the implementation of effective interventions was imperative. The major cause of high risk in pushing/pulling activities was attributed to the significant forces exerted on the worker, as well as his awkward postures. Engineering intervention involved the complete replacement of manual pushing and pulling by appropriate assistive devices proposed to lower the risk. In the case of MMH, the risk of injury was influenced by large trunk bending during lifting as well as the frequency of lifting. The interventions for MMH, therefore, focused on modifying bending conditions and lifting frequency. Both engineering and administrative interventions were proposed to mitigate these risks as follows.

3.2.1. Engineering Intervention:

1. Worktable: The first proposed intervention aimed to reduce excessive trunk bending during MMH tasks by using a worktable, which had no effect on pushing and pulling activities. The use of this worktable ensured that the load was positioned at a vertical distance of 85 cm and a horizontal distance of 50 cm from the middle of the worker's feet on the ground thus effectively reducing loading during lifting. An alternative approach involved using

roller conveyors instead of tables, which were beneficial when connecting the heat treatment (previous section) and shot-peening section.

2. Using lifting and moving overhead cranes: The utilization of overhead cranes facilitated the pushing and pulling of the carrier, while allowing for height adjustments, ensuring that filling and emptying occurred within an appropriate range. This equipment helped to prevent unnecessary trunk flexion through its height adjustments. Alternatively, motorized cranes were available thus eliminating the need for workers to exert force during pushing and pulling tasks. “Figure 5” displays the work environment following the implementation of interventions by an overhead crane and a worktable.

3.2.2. Administrative Intervention:

1. Team work: As all tools showed that the force applied to the worker exceeded the acceptable limits, and the frequency of lifting fell into hazardous ranges, one recommended solution was to introduce an additional worker to the shot-peening section. By implementing this intervention, the force exerted on each worker’s hands during pushing and pulling activities was effectively halved. Moreover, for lifting tasks, the number of lifts and lifting frequency could be reduced by up to 50% per day. This intervention mitigated issues related to overloading during pushing and pulling, as well as overuse during lifting. After shot-peening, it was crucial for the worker to carefully inspect and remove any remaining bullets on the shafts. This task added significant job stress. Using a second worker could be helpful by reducing the workload while also the number of parts that each worker needed to inspect decreased, leading to a reduction in errors.
2. Job rotation: Since this task encompassed three challenging components, it was suggested that job rotation be implemented in the workplace in case hiring an additional worker was not feasible. With this approach, the total daily working hours at this station could be reduced by half, and another worker participated an equal duration of work. Although the lifting frequency remained unchanged, the overall working time was halved.
3. The use of a shorter worker: Based on the biomechanical simulations conducted in this study, it was found that a shorter worker experiences smaller L5-S1 disc compression and shearing forces. Furthermore, a shorter worker would require smaller trunk bending while lifting the load.

3.3. Post-intervention risk re-assessments: After the proposed interventions were implemented a re-assessment of the risks was conducted. “Table 2” shows the states of risk re-assessments for each tool, while “Figure 4” shows the L4-L5 and L5-S1 disc compression forces after the interventions. By incorporating a worktable and adding a new worker, the values of the survival chance and the total cumulative damage were altered to 40.3% and 1.43, respectively. The second intervention, which involved using overhead cranes, proved to significantly reduce the risk of injury. This reduction was attributed to the reduced forces exerted on the worker when pulling the manual overhead crane’s chain or operating the motorized overhead crane's push button. These forces are similar to those experienced during normal daily activities.

4. Discussion

The investigated occupational activities in the present study posed a high risk of injury and involved significant compression loads on the L4-L5 and L5-S1 discs. To manage the risk of injury, five interventions were proposed (section 3.2). These interventions included using a worktable, implementing overhead cranes, hiring a second worker, adopting job rotation, and hiring shorter workers. Conducting a comprehensive biomechanical analysis of the occupational tasks required the simultaneous use of multiple biomechanical and ergonomic tools. This is because some tools consider specific parameters that others may not be able to consider. For example, Snook's tables do not take into account posture details and McGill’s Polynomial uses trunk moments as inputs without considering moment arm and distance of the hand-load. Additionally, certain ergonomic-based tools provide more systematic risk assessments using a broader range of input parameters; an advantage that can reduce the subjectivity of the risk assessments. However, it is important to acknowledge that these tools have some approximations in their assessment and their outcomes may also depend on the subjective judgment of the user (for instance, determination of the coupling multiplier in the NIOSH equation). Conversely, biomechanical tools, while valuable, tend to overlook the influence of loading frequency and time [38]. One limitation of the present study was the assessment of risk in a single male worker. Additionally, the worker’s posture could not be directly measured in the factory setting.

The worktable enabled shaft lifting without excessive bending, while the overhead cranes eliminated the need for pushing and pulling the carrier. Adding a second worker reduced the frequency of lifting and the forces required for carrier movement. Job rotation did not alter the lifting frequency but reduced the overall work time, thus distributing damage and risk between both workers. Shorter workers experienced smaller moments at their discs and require smaller trunk bending during lifting. Notably, McGill's Polynomial did not report a high risk for any of the activities, despite the clear presence of high-risk factors in the investigated occupational activities. In the lifting activity, the outputs of regression equations and AnyBody had the same trends. Similarly, in the pushing and pulling activities, AnyBody and 3DSSPP demonstrated a significant correlation "Figure 4". The most effective intervention was the implementation of the overhead cranes for pushing and pulling activities.

5. Conclusion

In the current study, the risk of injury was assessed in the lifting, pushing, and pulling tasks at Megamotor corporation shot-peening station using several biomechanical and ergonomics risk assessment tools. Almost all assessment tools reported high risk of musculoskeletal injuries thus highlighting the urgent need for effective interventions. The proposed interventions included the utilization of worktables, overhead cranes, additional worker, job rotation, and the recruitment of shorter workers. For all tasks, the dynamic loads in risk assessments were considered using D'Alembert's principle to calculate the exerted forces on workers' hands. The implementation of overhead cranes eliminated the necessity for manual pushing and pulling tasks, enabling workers to safely control these operations through either the overhead chain of the crane or the motorized overhead. This approach was deemed safe by all risk assessment tools.

Conflict of Interest

We have no conflicts of interest to disclose.

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References

[1] Schuttert, I., Timmerman, H., Petersen, K. K., et al., "The Definition, Assessment, and Prevalence of (Human Assumed) Central Sensitisation in Patients with Chronic Low Back Pain: A Systematic Review," *J Clin Med,* vol. 10, no. 24, p. 5931, doi: 10.3390/jcm10245931 (2021).

[2] Overas, C. K., Johansson, M. S., de Campos, T. F., et al., "Distribution and prevalence of musculoskeletal pain co-occurring with persistent low back pain: a systematic review," *BMC Musculoskelet Disord,* vol. 22, no. 1, p. 91, doi: 10.1186/s12891-020-03893-z (2021).

[3] Wang, L., Ye, H., Li, Z., et al., "Epidemiological trends of low back pain at the global, regional, and national levels," *European Spine Journal,* vol. 31, no. 4, pp. 953-962, doi: 10.1007/s00586-022-07133-x (2022).

[4] Chen, S. , Chen, M., Wu, X., et al., "Global, regional and national burden of low back pain 1990-2019: A systematic analysis of the Global Burden of Disease study 2019," *J Orthop Translat,* vol. 32, pp. 49-58, doi: 10.1016/j.jot.2021.07.005 (2022).

[5] Krishnan, K. S., Raju, G. and Shawkataly, O., "Prevalence of Work-Related Musculoskeletal Disorders: Psychological and Physical Risk Factors," *Int J Environ Res Public Health,* vol. 18, no. 17, p. 9361, doi: 10.3390/ijerph18179361 (2021).

[6] Govaerts, R., Tassignon, B., Ghillebert, J., et al., "Prevalence and incidence of work-related musculoskeletal disorders in secondary industries of 21st century Europe: a systematic review and meta-analysis," *BMC Musculoskelet Disord,* vol. 22, no. 1, p. 751, doi: 10.1186/s12891-021-04615-9 (2021).

[7] Anwer, S., Li, H., Antwi-Afari, M. F., et al., "Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: A systematic review," *International Journal of Industrial Ergonomics,* vol. 83, p. 103113, doi: 10.1016/j.ergon.2021.103113 (2021).

[8] Janevic, J., Ashton-Miller, J. A., and Schultz, A. B., "Large compressive preloads decrease lumbar motion segment flexibility," *J Orthop Res,* vol. 9, no. 2, pp. 228-36, doi: 10.1002/jor.1100090211 (1991).

[9] Andersson, G. B., "Epidemiologic aspects on low-back pain in industry," *Spine (Phila Pa 1976),* vol. 6, no. 1, pp. 53-60, doi: 10.1097/00007632-198101000-00013 (1981).

[10] Andersson, G. B., "Epidemiological features of chronic low-back pain," *Lancet,* vol. 354, no. 9178, pp. 581-5, doi: 10.1016/S0140-6736(99)01312-4 (1999).

[11] Ghafouri, M., Teymourzadeh, A., Nakhostin-Ansari, A., et al., "Prevalence and predictors of low back pain among the Iranian population: Results from the Persian cohort study," *Annals of Medicine and Surgery,* vol. 74, p. 103243, doi: 10.1016/j.amsu.2022.103243 (2022).

[12] Hartvigsen, J., Hancock, M. J., Kongsted, A., et al., "What low back pain is and why we need to pay attention," *Lancet,* vol. 391, no. 10137, pp. 2356-2367, doi: 10.1016/S0140-6736(18)30480-X (2018).

[13] Hoy, D., Bain, C., Williams, G., et al., "A systematic review of the global prevalence of low back pain," *Arthritis Rheum,* vol. 64, no. 6, pp. 2028-37, doi: 10.1002/art.34347 (2012).

[14] Maher, C., Underwood, M., and Buchbinder, R., "Non-specific low back pain," *Lancet,* vol. 389, no. 10070, pp. 736-747, doi: 10.1016/S0140-6736(16)30970-9 (2017).

[15] Basakci Calik, B., Yagci, N., Oztop, M., et al., "Effects of risk factors related to computer use on musculoskeletal pain in office workers," *Int J Occup Saf Ergon,* vol. 28, no. 1, pp. 269-274, doi: 10.1080/10803548.2020.1765112 (2022).
[16] Rezaei, B., Mousavi, E., Heshmati, B., et al., "Low back pain and its related risk factors in health care providers at hospitals: A systematic review," *Annals of medicine and surgery,* vol. 70, p. 102903, doi: 10.1016/j.amsu.2021.102903 (2021).
[17] Wong, C. K., Mak, R. Y., Kwok, T. S., et al., "Prevalence, Incidence, and Factors Associated With Non-Specific Chronic Low Back Pain in Community-Dwelling Older Adults Aged 60 Years and Older: A Systematic Review and Meta-Analysis," *J Pain,* vol. 23, no. 4, pp. 509-534, doi: 10.1016/j.jpain.2021.07.012 (2022).
[18] Katz, J. N., "Lumbar disc disorders and low-back pain: socioeconomic factors and consequences," *J Bone Joint Surg Am,* vol. 88 Suppl 2, no. suppl_2, pp. 21-4, doi: 10.2106/JBJS.E.01273 (2006).
[19] Dutmer, A. L., Schiphorst Preuper, H. R., Soer, R., et al., "Personal and Societal Impact of Low Back Pain: The Groningen Spine Cohort," *Spine (Phila Pa 1976),* vol. 44, no. 24, pp. E1443-E1451, doi: 10.1097/BRS.0000000000003174 (2019).
[20] Waters, T. R., Putz-Anderson, V., and Garg, A., "Applications manual for the revised NIOSH lifting equation," doi: 10.26616/NIOSHPUB94110revised092021 (1994).
[21] McAtamney, L., and Nigel Corlett, E., "RULA: a survey method for the investigation of work-related upper limb disorders," *Appl Ergon,* vol. 24, no. 2, pp. 91-9, doi: 10.1016/0003-6870(93)90080-s (1993).
[22] McAtamney L., and Hignett, S., "Rapid Entire Body Assessment (REBA) Applied Ergonomic," ed: 1st, DL Kimbler. Clemson University (2000).
[23] Rajaee, M. A., Arjmand, N., Shirazi-Adl, A., et al., "Comparative evaluation of six quantitative lifting tools to estimate spine loads during static activities," *Appl Ergon,* vol. 48, pp. 22-32, doi: 10.1016/j.apergo.2014.11.002 (2015).
[24] Fazi, H. B. M., Mohamed, N. M. Z. B. N. and Basri, A. Q. B., "Risks assessment at automotive manufacturing company and ergonomic working condition," in *IOP Conference Series: Materials Science and Engineering*, vol. 469, no. 1: IOP Publishing, p. 012106, doi: 10.1088/1757-899X/469/1/012106 (2019).
[25] Deros, B. M., Daruis, D. D. I., Rosly, A. L., et al., "Ergonomic risk assessment of manual material handling at an automotive manufacturing company," *PressAcademia Procedia,* vol. 5, no. 1, pp. 317-324, doi: 10.17261/Pressacademia.2017.606 (2017).
[26] Skals, S., Blafoss, R., Andersen, L. L., et al., "Manual material handling in the supermarket sector. Part 2: Knee, spine and shoulder joint reaction forces," *Appl Ergon,* vol. 92, p. 103345, doi: 10.1016/j.apergo.2020.103345 (2021).
[27] Calculator, W. L., "Washington State Department of Labor and Industries", https://www.lni.wa.gov.
[28] Pinder, A. D., *Benchmarking Manual Handling Assessment Charts (MAC)*. Health and Safety Laboratory (2002).
[29] Snook, S. H. and Ciriello, V. M., "The design of manual handling tasks: revised tables of maximum acceptable weights and forces," *Ergonomics*, vol. 34, no. 9, pp. 1197-213, doi: 10.1080/00140139108964855 (1991).
[30] Burgess-Limerick, R., Straker, L., Pollock, C., et al., "Manual Risk Assessment Tool (ManTRA) V2. 0," *School of Human Movement Studies. The University of Queensland, Australia* (2004).

[31] David, G., Woods, V., Li, G., et al., "The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders," *Appl Ergon*, vol. 39, no. 1, pp. 57-69, doi: 10.1016/j.apergo.2007.03.002 (2008).

[32] Coenen, P., Kingma, I., Boot, C. R., et al., "The contribution of load magnitude and number of load cycles to cumulative low-back load estimations: a study based on in-vitro compression data," *Clin Biomech (Bristol, Avon)*, vol. 27, no. 10, pp. 1083-6, doi: 10.1016/j.clinbiomech.2012.07.010 (2012).

[33] Scott, G. B., and Lambe, N. R., "Working practices in a perchery system, using the OVAKO Working posture Analysing System (OWAS)," *Appl Ergon*, vol. 27, no. 4, pp. 281-4, doi: 10.1016/0003-6870(96)00009-9 (1996).

[34] Arjmand, N., Plamondon, A., Shirazi-Adl, A., et al., "Predictive equations to estimate spinal loads in symmetric lifting tasks," *J Biomech*, vol. 44, no. 1, pp. 84-91, doi: 10.1016/j.jbiomech.2010.08.028 (2011).

[35] McGill, S. M., Norman, R. W., and Cholewicki, J., "A simple polynomial that predicts low-back compression during complex 3-D tasks," *Ergonomics*, vol. 39, no. 9, pp. 1107-1118, 1996, doi: 10.1080/00140139608964532 (1996).

[36] Yamaguchi, G. T., *Dynamic modeling of musculoskeletal motion: a vectorized approach for biomechanical analysis in three dimensions*. Springer Science & Business Media (2005).

[37] Harmon, M., and Lewis, R., "Review of top of rail friction modifier tribology," *Tribology-Materials, Surfaces & Interfaces*, vol. 10, no. 3, pp. 150-162, doi: 10.1080/17515831.2016.121626 (2016).

[38] Eynipour, A., Arjmand, N., Dianat, I., et al., "Assessing Musculoskeletal Disorder Risks in an Automobile Part Manufacturing Factory: A Comparison Study of Biomechanical and Ergonomic Tools," *Health Scope*, vol. 13, no. 2, doi: 10.5812/healthscope-139610 (2024).

Figure 1. The most critical instances of the a) lifting, b) pushing and c) pulling activities.

Figure 2. While most of the tools are developed to determine the risk of injury during the lifting activity, only few are useful for the assessment of the pushing and pulling activities.

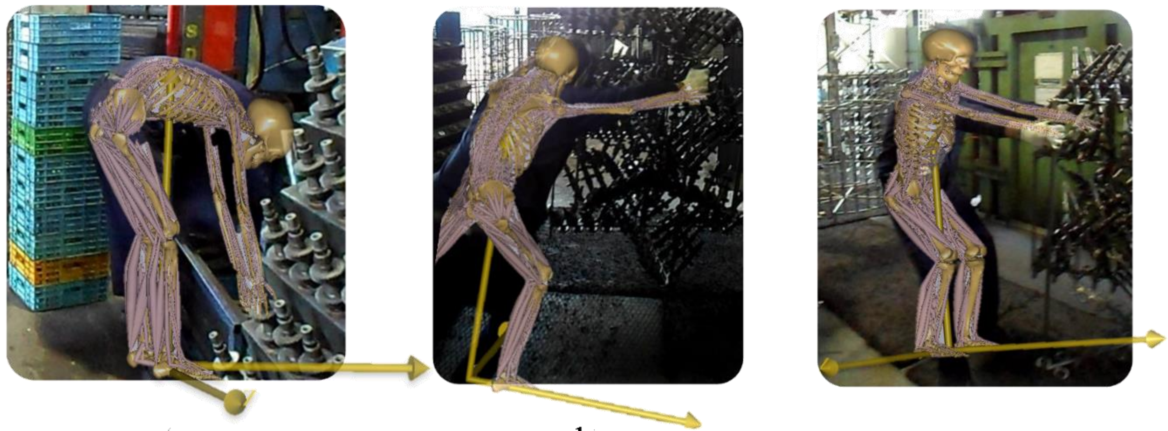
Figure 3. Simulated postures using the biomechanical risk assessment tools.

Figure 4. Predicted disc (L4-L5 or L5-S1) compression loads using biomechanical tools for the critical posture of the investigated occupational activities with and without interventions.

Figure 5. Workspace after interventions by applying a worktable and overhead crane.

Table 1. Job characteristics

Table 2. Level of risk of injury for the critical posture of the investigated occupational activities using various risk assessment tools. A dash line was used when a tool was unable to assess the risk or when certain interventions did not have any impact on the risk assessment tools.



a b c

Figure 1

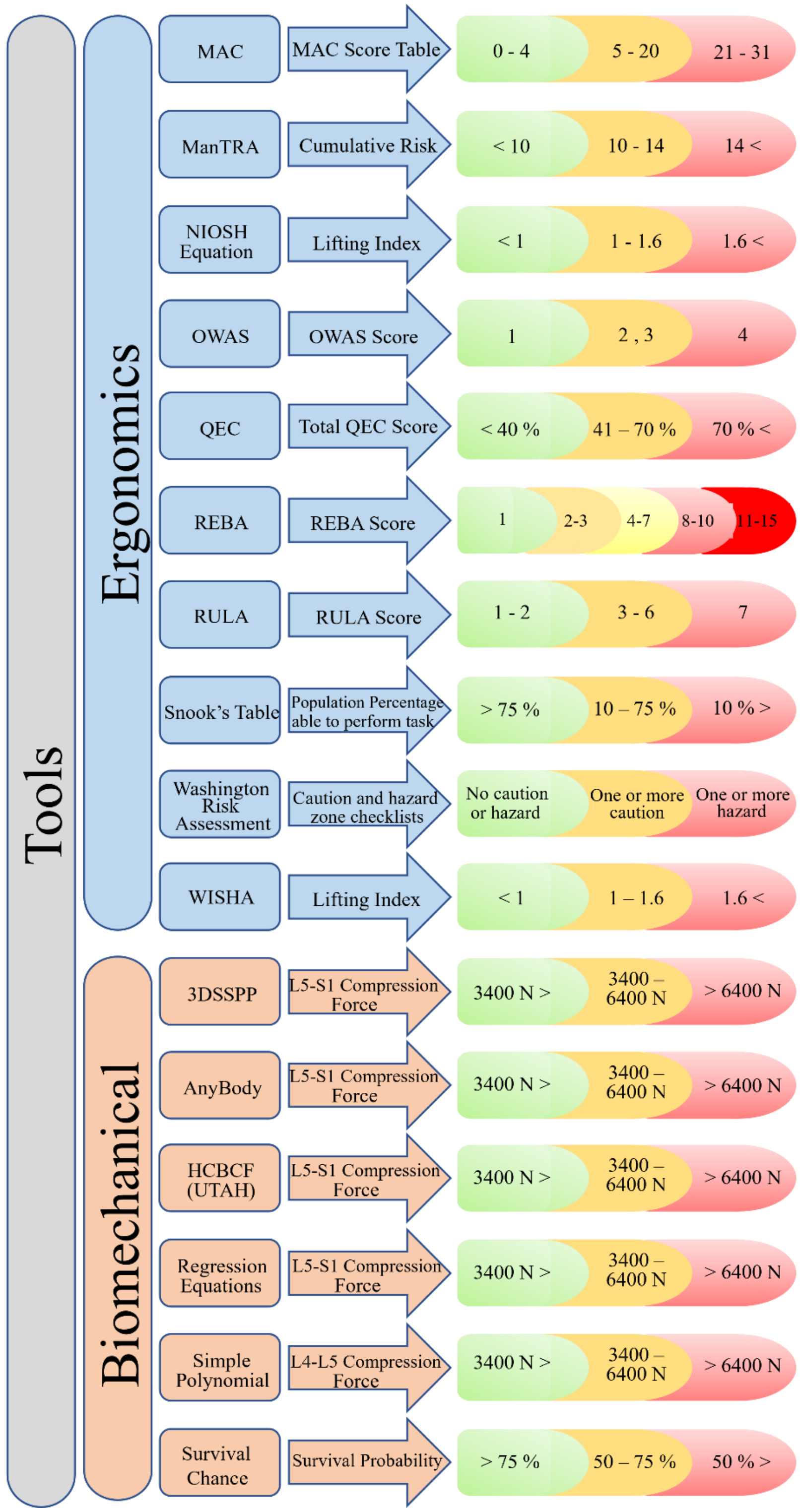

Tools
Ergonomics
MAC
MAC Score Table
0 - 4
5 - 20
21 - 31
ManTRA
Cumulative Risk
< 10
10 - 14
14 <
NIOSH Equation
Lifting Index
< 1
1 - 1.6
1.6 <
OWAS
OWAS Score
1
2 , 3
4
QEC
Total QEC Score
< 40 %
41 – 70 %
70 % <
REBA
REBA Score
1
2-3
4-7
8-10
11-15
RULA
RULA Score
1 - 2
3 - 6
7
Snook's Table
Population Percentage able to perform task
> 75 %
10 – 75 %
10 % >
Washington Risk Assessment
Caution and hazard zone checklists
No caution or hazard
One or more caution
One or more hazard
WISHA
Lifting Index
< 1
1 – 1.6
1.6 <
Biomechanical
3DSSPP
L5-S1 Compression Force
3400 N >
3400 – 6400 N
> 6400 N
AnyBody
L5-S1 Compression Force
3400 N >
3400 – 6400 N
> 6400 N
HCBCF (UTAH)
L5-S1 Compression Force
3400 N >
3400 – 6400 N
> 6400 N
Regression Equations
L5-S1 Compression Force
3400 N >
3400 – 6400 N
> 6400 N
Simple Polynomial
L4-L5 Compression Force
3400 N >
3400 – 6400 N
> 6400 N
Survival Chance
Survival Probability
> 75 %
50 – 75 %
50 % >

Figure 2

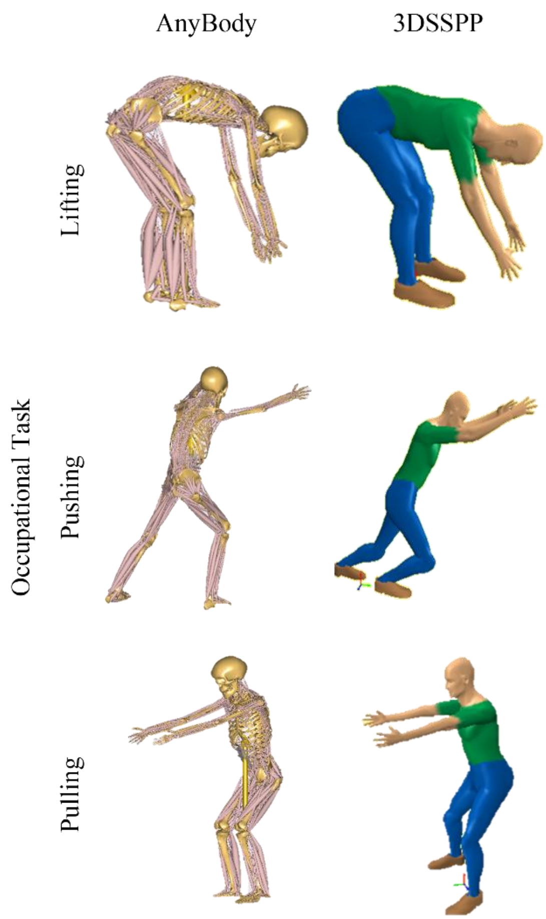

AnyBody
3DSSPP
Occupational Task
Lifting
Pushing
Pulling

Figure 3

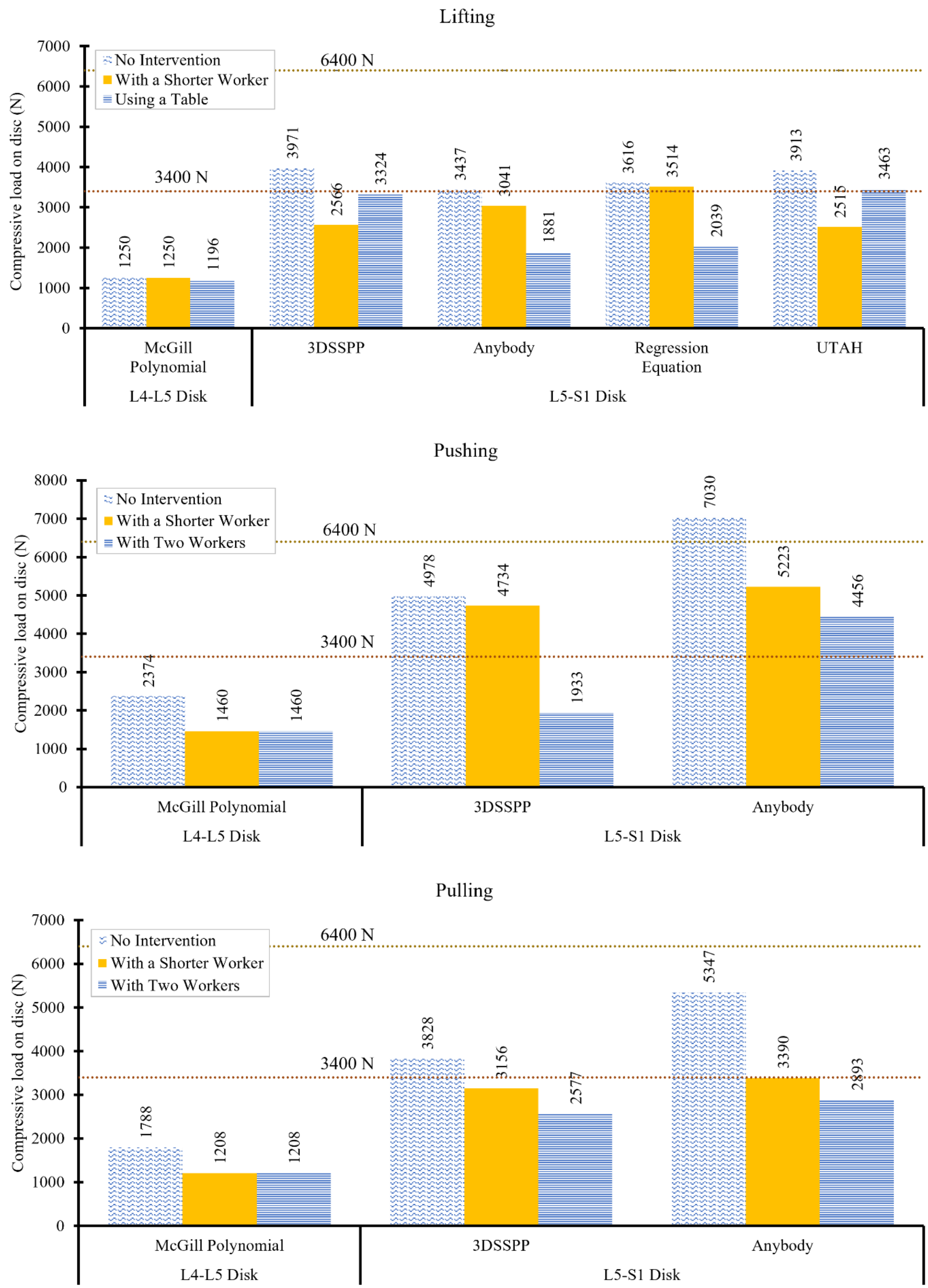

Lifting
No Intervention
With a Shorter Worker
Using a Table
6400 N
3400 N
Compressive load on disc (N)
7000
6000
5000
4000
3000
2000
1000
0
1250
1250
1196
3971
2566
3324
3437
3041
1881
3616
3514
2039
3913
2515
3463
McGill Polynomial
3DSSPP
Anybody
Regression Equation
UTAH
L4-L5 Disk
L5-S1 Disk
Pushing
No Intervention
With a Shorter Worker
With Two Workers
6400 N
3400 N
Compressive load on disc (N)
8000
7000
6000
5000
4000
3000
2000
1000
0
2374
1460
1460
4978
4734
1933
7030
5223
4456
McGill Polynomial
3DSSPP
Anybody
L4-L5 Disk
L5-S1 Disk
Pulling
No Intervention
With a Shorter Worker
With Two Workers
6400 N
3400 N
Compressive load on disc (N)
7000
6000
5000
4000
3000
2000
1000
0
1788
1208
1208
3828
3156
2577
5347
3390
2893
McGill Polynomial
3DSSPP
Anybody
L4-L5 Disk
L5-S1 Disk

Figure 4

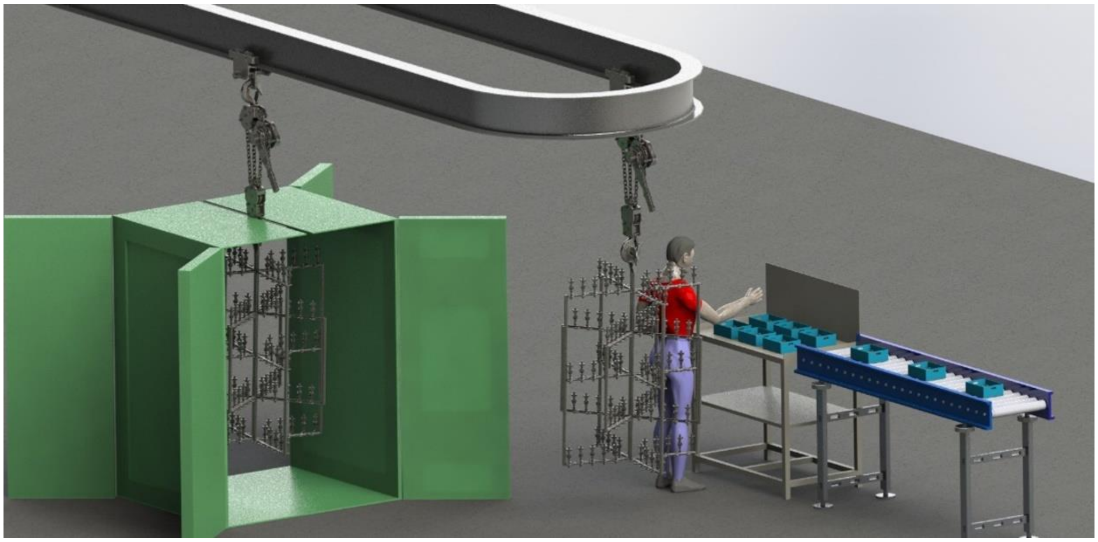


Figure 5

Table 1

Occupational Activity	Characteristic	Quantity
Lifting	Hands load weight	6.788 kg
	Horizontal distance	55 cm
	Vertical distance	30 cm
	Duration of the activity	8 hours per day
	Frequency	6 times per minute
	Acceleration	1 m/s^2
Pushing and pulling	Hands load	670 N
	Frequency	11 times per day
	Acceleration	0.5 m/s^2
	Maximum travel distance	2 m

Table 2

Job Activity	Tools	No Intervention	Interventions				
			Administrative		Administrative		
			Shorter Worker	Job Rotation	Employing 2 Workers	Overhead Cranes	Worktable
Lifting (MMH)	3DSSPP	Moderate	Low	-	-	-	Low
	AnyBody	Moderate	Low	-	-	-	Low
	HCBCF	Moderate	Low	-	-	-	Low
	MAC	High	Low	-	Low	Low	-
	ManTRA	High	Low	-	Low	Low	-
	NIOSH equation	High	High	-	Moderate	Moderate	-
	OWAS	Moderate	Low	-	Moderate	Moderate	-
	QEC	High	High	-	High	Moderate	-
	REBA	High	Moderate	-	High	High	-
	Regression Equations	Moderate	Low	-	-	-	Moderate
	RULA	High	Moderate	-	-	-	-
	Simple polynomial	Low	Low	-	-	-	Low
	Snook's Table	High	Moderate	-	Moderate	Moderate	-
	Washington State Risk Assessment	High	High	-	-	-	-
	WISHA	High	Moderate	-	Low	High	-
Pushing	3DSSPP	High	-	Low	Low	-	High
	AnyBody	High	-	Low	Moderate	-	Moderate
	ManTRA	Low	-	Low	Low	Low	-
	OWAS	Moderate	-	Low	Moderate	Moderate	-
	QEC	Moderate	-	Low	Moderate	Moderate	-
	REBA	High	-	Low	High	High	-
	RULA	High	-	Low	-	-	-
	Simple polynomial	Low	-	Low	-	-	Low
	Snook's Table	High	-	Low	High	Moderate	-
Pulling	3DSSPP	Moderate	-	Low	Low	-	Low
	AnyBody	High	-	Low	Low	-	Low
	ManTRA	Low	-	Low	Low	Low	-
	OWAS	Moderate	-	Low	Moderate	Moderate	-
	QEC	Moderate	-	Low	Moderate	Moderate	-
	REBA	High	-	Low	High	High	-
	RULA	High	-	Low	-	-	-
	Simple polynomial	Low	-	Low	-	-	Low
	Snook's Table	High	-	Low	Moderate	Moderate	-

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